Renewable and Sustainable Energy Reviews 15 (2011) 4788–4796

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of heat pump systems for drying application

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ARTICLE INFO

Article history:
Received 17 February 2011
Received in revised form 10 April 2011
Accepted 5 July 2011
Available online 22 September 2011

Keywords:
Heat pump systems
Quality of dried products
Quality of air
Solar energy
COP

ABSTRACT

Heat pump system has been research and developed for different applications and mostly in space heating, cooling and dehumidifying (drying). To improve the performance of the heat pump system, research on modifying heat pump system and combining to other mechanism has been done widely. Heat pump dryer is proven as drying system that ensure the product's quality especially food and agriculture products, able to control drying temperature, relative humidity, moisture contain extraction, drying air velocity, drying period and etc. Factor to be concern in improving a heat pump dryer includes the installation cost, drying performance such as air velocity, drying temperature and relative humidity, performance of the component hybrid to heat pump dryer, power required to run the system and also payback period. By improving the development of heat pump dryer will help increase the product quality and reducing operation cost of drying industry.

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1. Introduction

Drying preserves the product by lowering the amount of moisture in the material, while freezing preserves the product by lowering its temperature below the freezing point of water [1]. The drying technique permits early harvest, planning the harvest season, lighter weight for transportation and less space for long time storage without deterioration [2]. Drying methods include convention, solar, oven, dehydrator and heat pump system. Drying of various products using heat pump system will be discussed in this paper. Heat pump is an efficient heating and cooling generating system. Application of heat pump in residential can be seen as existing refrigeration and air conditioning systems. Peter Ritter von Rittinger develops and builds the first heat pump [3]. There are various designs of heat pump system for different application but the main components of heat pump still made up of compressor, condenser, expansion valve, evaporator and refrigerant.

2. Heat pump

Heat pump had been researched and developed for a long time to improve the performance. Heat pump had been modified to gas-engine-driven heat pump [4], ground source heat pump (GSHP) [5], solar heat pump [6], photovoltaic/thermal (PV/T) heat pump [7,8], chemical eat pump [9,10], and desiccant heat pump [11–13]. Classification of recent development in heat pump system is elaborate in energy efficiency, hybrid system and applications by Chua et al. [27] as shown in Fig. 1. Applications for heat pump systems are widely used in space heating and cooling, desalination and drying. The main advantages of using HP technology are the energy

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doi:10.1016/j.rser.2011.07.072

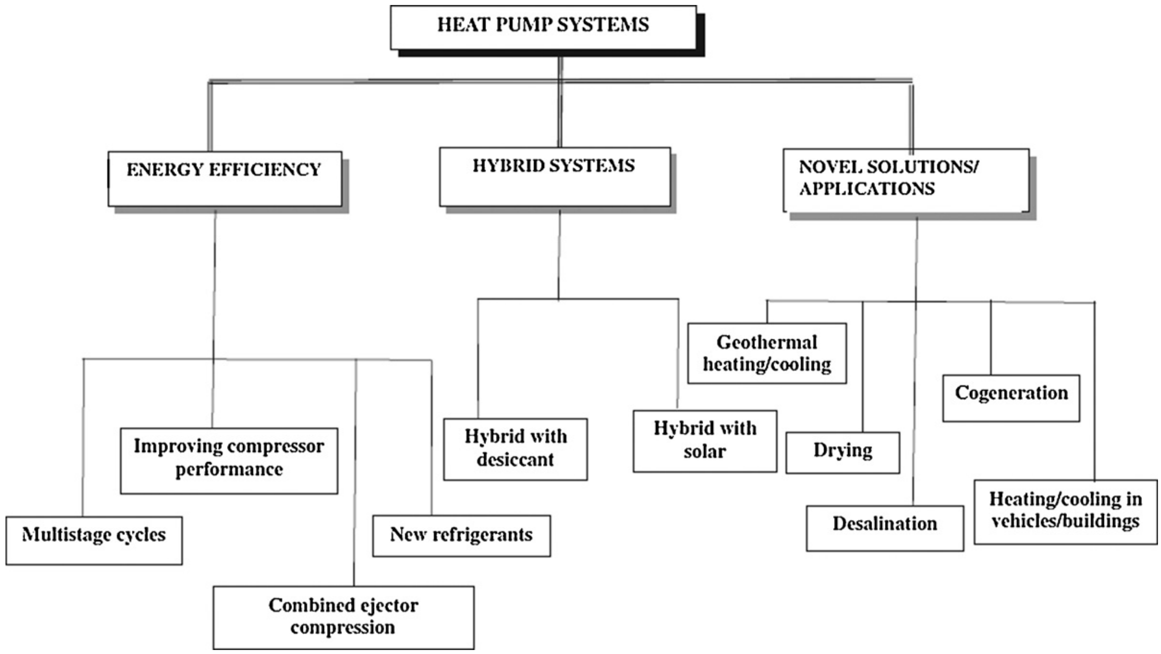


Fig. 1. Classification of heat pump development [27].

saving potential and the ability to control drying temperature and air humidity. This creates the possibility of a wide range of drying conditions [19]. Using a heat pump dryer, which is a combination of heat pump and drying unit, both the latent heat and sensible heat can be recovered from the exhaust air, thus improving the overall thermal performance and yielding effective control of air conditions at the inlet of the dryer [20]. Energy savings of about 40% were reported using heat pump dryers as compared to electrical resistance dryers [21,22]. The heat pump drying technology is suitable for high value products and its ability to produce controlled transient drying conditions in terms of temperature, humidity, and air velocity has been investigated in order to improve product quality and reduce drying cost [23]. A detailed mathematical model to investigate the performance of a heat-pump assisted drying system was reported by Pendyala et al. [24] and Xiguo Jia et al. [25].

The idea of solar assisted heat pump (SAHP) was first introduced by Sporn and Ambrose [28]. Evaluation of rice drying had been tested with a SAHP dryer with 34.9 °C of drying temperature and achieves 34.4% of relative humidity [29]. Other researchers had also conducted experimental works on SAHP in different climate region that contributed to the photo thermal utility of solar energy and the thermal performance of heat pump system [30,31]. Saitoh studied the performance of a glazed sheet-and-tube PV/T collector using brine as the heat removal fluid; this collector was shown to have higher exergy efficiency than the case with a PV module and a solar thermal collector being placed side by side [32]. But another research suggest that replace refrigerant with brine as cooling to the photovoltaic (PV) would show higher efficiency on the PV since the brine water tank would reach high temperature after collecting the heat [7].

3. Heat pump dryer

The main objective of any drying process is to produce a dried product of desired quality at a minimum cost and maximum throughput by optimizing the design and operating conditions [14]. Drying is one of the most energy intensive unit operations that easily account for up to 15% of all industrial energy utilizations [15]. In many industrial drying processes, a large fraction of energy is wasted [16]. Drying process consumes up to 70% of the total energy in manufacturing wood products, 50% of the total energy consumption in the manufacturing of finished textile fabrics and over 60% of the total energy needed for on farm corn production [17]. Drying is an energy-intensive operation consuming 9–25% of national energy in the developed countries [18]. Thus, to reduce energy consumption per unit of product moisture, it is necessary to scrutinize different methodologies to improve the energy efficiency of the drying equipment [17]. In Japan [26], a simulation study of district cooling/heating systems using sewage water as an energy source shows that, compared with conventional air-source heat pumps, wastewater source heat pumps could help reducing energy consumption by 34%, lowering the emission of carbon dioxide ($CO2$) by 68% and controlling the generation of nitrogen oxides (NOx) by 75% [26]. Many researcher has agreed on using heat pump dryer help improve drying quality and produce a range of precise condition [82,83].

3.1. *Solar assisted (hybrid) heat pump dryer*

Hybrid solar technology and heat pump system is to improve PV performance and collect heat from the PV. A PV/T collector combines with heat pump's evaporator had been done by Jie Ji et al. [8]. Saensabai and Prasertsan compare on 5 different component arrangements in heat pump dryer configuration [77]. COP of heat pump can achieve as high as 4–5 but to achieve optimum performance, the system configuration must be changed according to the changing property of the working fluid [78–80]. According to Saensabai and Prasertsan, condenser is a vital component in a heat pump drying system [81]. They also found that by changing the refrigerant flow path can improve COP to 27.6% and 12.3% by increasing coil depth (Fig. 2).

A solar heat pump dryer (SHPD) with 1.5 kW capacity of compressor that produced hot water and hot air for agriculture product drying was constructed as shown in Fig. 3. Air flow is dried by solar collector and condenser. An auxiliary heater is fixed after condenser and will be used if higher drying temperature is required which was determined by the magnitude of the desired dryer inlet temperature and the meteorological conditions. Agriculture product

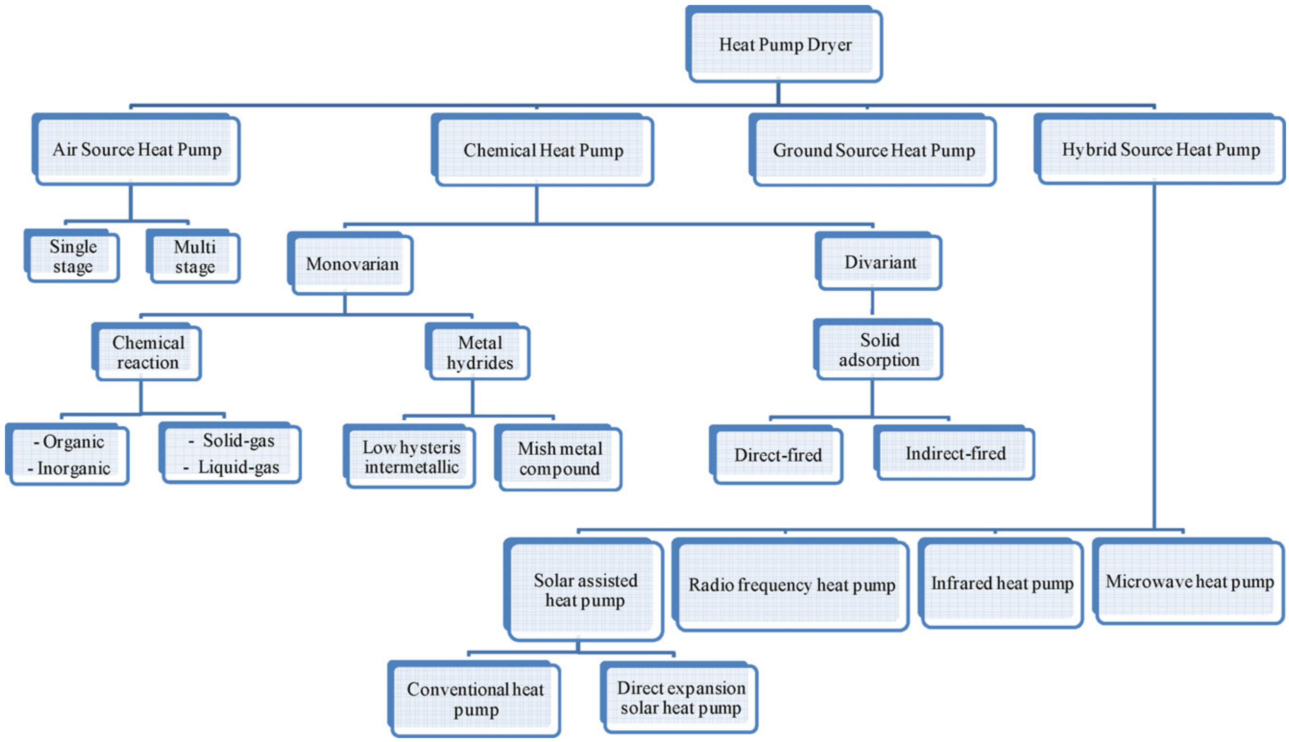


Fig. 2. Classification of heat pump dryers [10,76].

dried in the research is green bean. Mass flow rate of air is set to 0.06 kg/s and the product was dried under drying temperature of 45 °C, 50 °C and 55 °C. The corresponding experimental value COP of 6.45 is obtained under this condition. From the research, specific moisture extraction rate (SMER) declined with proportional to drying time. An SMER of 0.97 is observed for 30 kg sample, whereas SMER values of 0.65 and 0.16 are obtained for the weights 20 kg and 5 kg, respectively (Table 1).

3.2. Air source heat pump dryer

Air source heat pump dryer uses normal heat pump system with evaporator as dehumidifier and condenser as heater. Prasertsan and Saensabai experimented on 5 different configurations of air source heat pump by simulation [77]. Another air source heat pump dryer had been constructed and study with agriculture product by Pal, Khan and Mohanty [36]. A research done on comparing a fluid bed

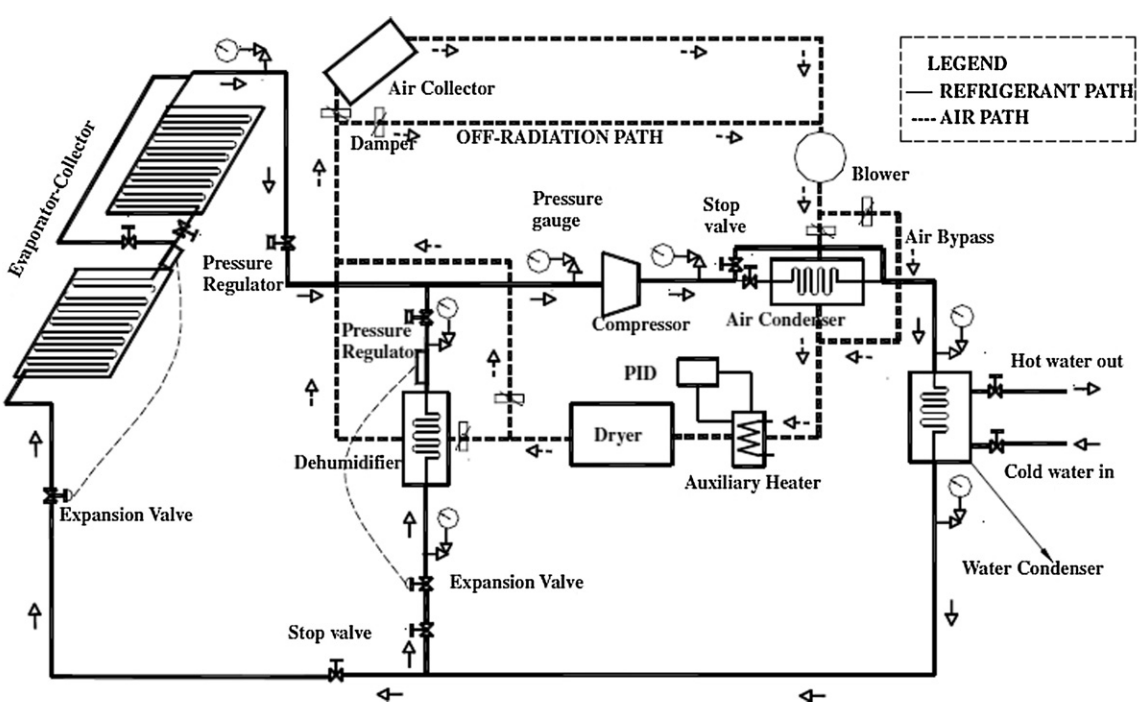


Fig. 3. Solar assisted heat pump dryer [74].

Table 1
Various heat pump dryer research on different products.

Application	Product	Drying system	Drying temperature (°C)
Agriculture	Broccoli Floret [33]	Dual condenser vapor compression cycle	60
	Chili [34]	Vacuum heat pump	50–65
	Green sweet pepper [36]	Dual condenser vapor cycle	35
	Kaffir leaf [37]		40–60
	Shitake mushroom [38]	Vacuum heat pump	50–65
	Olive leaf [39]	Dual condenser vapor compression cycle	53.43
	Rice [40]	Solar assisted vapor compression cycle	30.8–34
	Lemon [41]	Vapor compression cycle	60
	Tomato [22]	Dual condenser vapor compression cycle	40–50
	Macadamia nut [55]	Air source heat pump	50
	Red pepper [57]	Atmospheric freezer heat pump	−3 to 20
	Grain (cereal) [61]	Air source heat pump	
	Vegetables [62]	Air source heat pump	
	Specialty crops [66]	Heat pump with flow bed	30–45
	Mint leave [72]	Ground source heat pump	40, 45, 50
	Green bean [74]	Solar heat pump	40, 45, 50
Fruit	Grape [42]	Vapor compression cycle	50–60
	Apple [43]	Vapor compression cycle	40
	Apple [44]	Dual condenser vapor compression cycle	60–80
	Guava [44]	Dual condenser vapor compression cycle	60–80
	Guava [45]	Two stage heat pump	30–35
	Banana [45]	Two stage heat pump	30–35
	Papaya [46]	Dual condenser vapor compression cycle	55
	Mango [46]	Dual condenser vapor compression cycle	55
	Banana [47]		50
	Peas [48]	Dual condenser vapor compression cycle	20–60
	Sapota [49]	Dual condenser vapor compression cycle	40–60
	Nectarine [59]	Air source heat pump	25
Herbs			
	Ginger [35]	Vapor compression cycle	40–60
	Jew's mallow [1]	Heat pump with honeycomb for homogeneous air distribution	45–55
	Spearmint [1]		
	Parsley [1]		
	Laurel (Bay) leaves [75]	Ground source heat pump	40–50
Marine	Horse Mackerel [50]		20–30
Food	Cheese [51]	Low temperature heat pump drying	12
	Instant food (cranberry + potato) [52]	CO_2 heat pump dryer	−10 to 30
	Chicken meat [58]	Superheated steam with heat pump	55
Wood	Wood [53]	Air Source heat pump	82.2–93.3
	Wood chip [54]	Single-stage absorption heat pump	40–43
	Wood [56]	Air Source heat pump	–
	Timber [60]	Air source heat pump	–
	Paper [65]	Air source heat pump	–
Other	Foam rubber [63]	Air source heat pump	–
	Granular food and biotechnological [64]	Freezer with fluidized bed heat pump	−20 to 50
	Ceramic [67]	Chemical heat pump	75
	Protein [68]	Atmospheric freezer heat pump	−5
	Sludge [69]	Solar heat pump	35
	Wool [70]	Air Source heat pump	60
	Wool [71]	Air Source heat pump	60
	Clothes [73]	Air Source heat pump	80–130

dryer and an air source heat pump dryer using agriculture product as shown in Fig. 4. The mass flow rate determined in the research are 0.5, 1.0 and 1.5 m/s while the temperature are 45, 50, 55 °C. The comparison shows that air source heat pump dryer give better performance than fluid bed with drying temperature above 50 °C. Relative humidity of heat pump dryer gives 9.4–14.6%.

3.3. Ground source heat pump dryer

The US Environmental Protection Agency (USEPA) estimated that geothermal heat pumps can reduce energy consumption by up to 44% compared to air-source heat pumps and up to 72% compared to conventional electrical heating and air conditioning [84]. For most areas of the US, geothermal heat pumps are the most energy-efficient means of heating and cooling buildings [85]. Across Europe, hundreds of thousands of domestic heat pump units are in use, and the technology is tried, tested and reliable [86]. Fig. 5 shows a ground-source heat pump dryer [87].

3.4. Heat pump assisted (hybrid) microwave drying

Heat pump assisted microwave system is one of the hybrid systems with heat pump in drying technology. The first studies on combining HPs and microwave drying were proposed in the literature by Lawton [88], and Metaxas and Meredith [89]. Jia et al. [90] had tested on overall performance of heat pump hybrid microwave drying system. A prototype dryer with 5 kW of heat pump compressor and 10 kW microwave power was constructed in the experiment as shown in Fig. 6. The results of the study indicated that with careful design heat pump assisted microwave

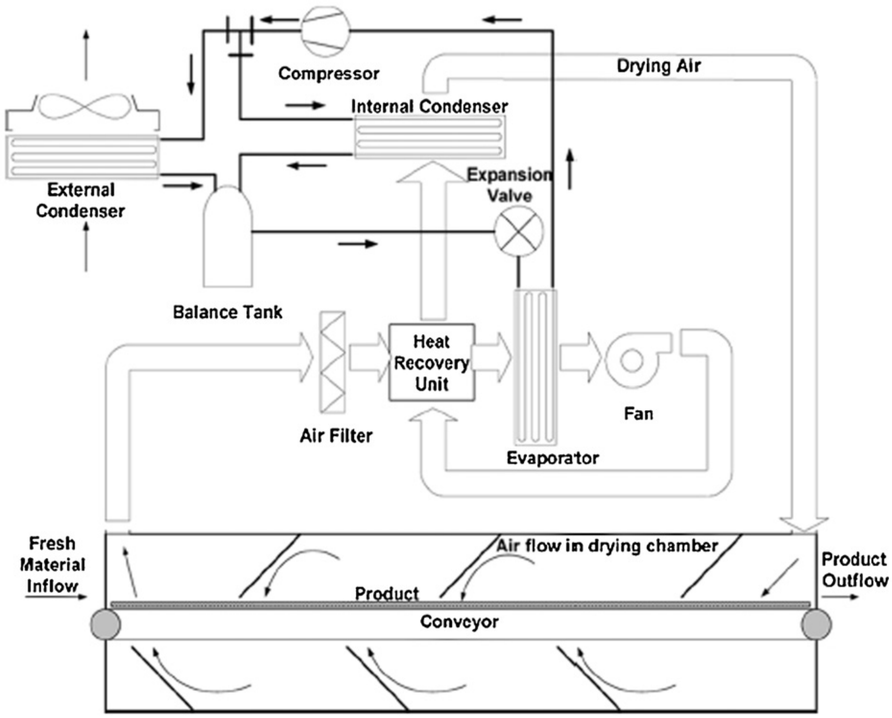


Fig. 4. Air source heat pump dryer [33].

drying is comparable to conventional convective drying in energy consumption.

3.5. Chemical heat pump dryer

Although heat pump is favored to be research and developed as to provide cooling and heating, chemical heat pump had gain attention in recent years [91–93]. CHP absorbs energy via endothermic and release energy via exothermic in the form of chemical. CHP systems utilize the reversible chemical reaction to change the temperature level of the thermal energy, which stored by chemical substances [94]. These chemical substances are important in absorb and release heat energy [95]. Various chemical substance can be use in CHP for chemical reaction, for examples, water system (hydroxide/oxide, salt hydrate/salt or salt hydrate), ammonia system (ammoniate/ammoniate or salt, amine complex with salt), sulfur dioxide system (sulphite/oxide, phyrosulphate), carbon dioxide system (carbonate/oxide, barium oxide/barium carbonate), hydrogen system (hydride or metal, hydrogenation/dehydrogenation), etc. has been proposed as working medium [10]. Sharonov and Aristov had performed thermodynamic analysis and cycle efficiency on an ideal cycle of chemical and adsorption heat pumps by simulations [96]. Categories of CHP systems had been illustrate in Figs. 1 and 7 shows a simple CHP cycle. A catalyst-assisted CHP was developed by Saito, Kameyama and Yoshida for upgrading low-level energy [97]. This catalyst-assisted

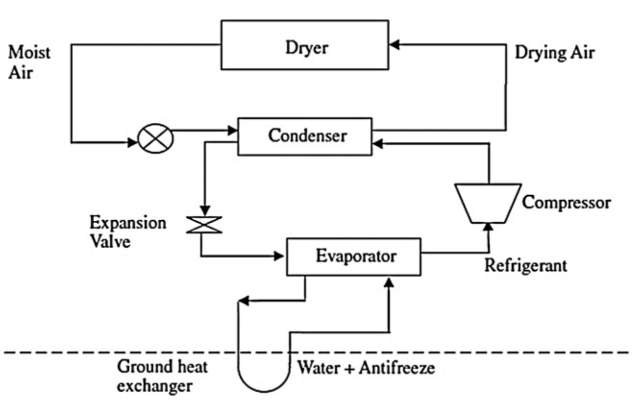


Fig. 5. Ground source heat pump dryer [87].

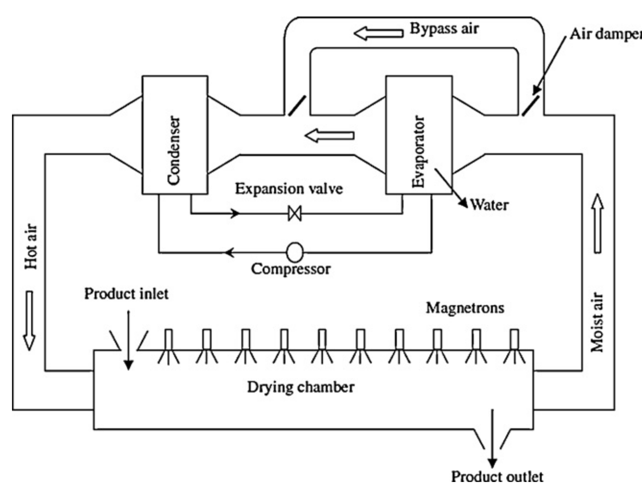


Fig. 6. Heat pump assisted microwave dryer [90].

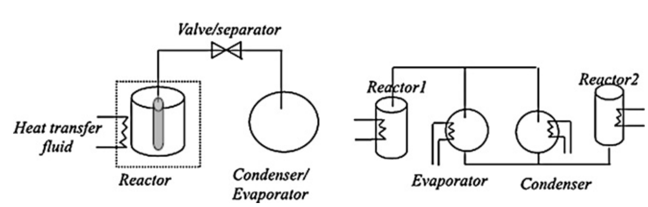


Fig. 7. Simple CHP cycle [10].

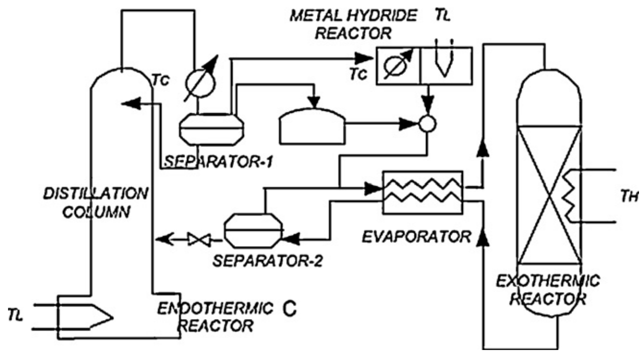


Fig. 8. Catalyst-assisted CHP [97].

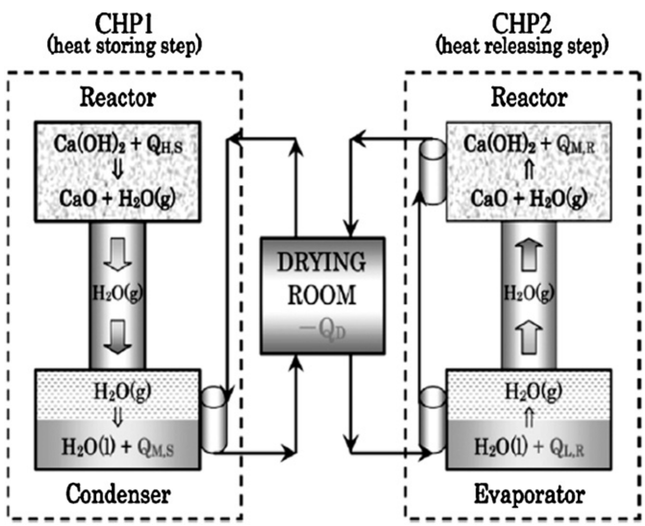
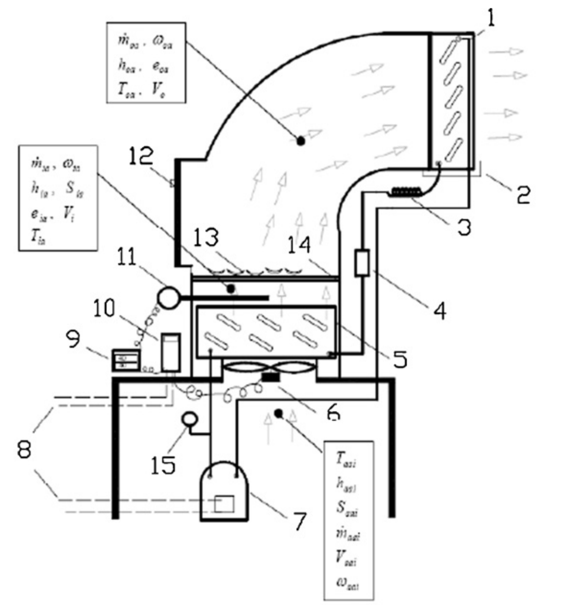


Fig. 9. CHP dryer [98].

CHP produced high temperature of about 200 °C, rate of reaction of 0.98 and rate of hydrogen to acetone as 5 with the maximum COP of 0.36. Fig. 8 shows a of continuous type liquid–gas CHP where high temperature of exothermic reaction is produced and low temperature of endothermic reaction heat are supplied for decomposition of metal hydride [97]. Fig. 9 shows a CHP dryer using $CAO/H_2O/Ca(OH)_2$ reaction in heat enhancement for drying systems [98].



1. Evaporator 2. Condensated water 3. Capillary tube 4. Dryer filter 5. Condenser 6. Axial fan 7. Compressor 8. Power supply 9. Process control equipment 10. Invertor (AC variable speed drive) 11. Thermocouple (T, pt-100) 12. Lid 13. Sliced 14. Shelf 15. Manometer

Fig. 10. Heat pump with PID control.

3.6. Other hybrid HPD systems

There are several of combinations or hybrid system of HP dryer with other technology such as heat pump hybrid solar, microwave, radio frequency, or infrared that provides different performances and requirements. By adding some equipment or configuration of some parameter will also help improved drying system. Ceylan study the performances on kiwi, banana and avocado drying with PID control heat pump [99]. The experiment runs with mean air velocity of 0.37 m/s and air drying temperature of 40 °C. Fig. 10 shows the heat pump dryer wit PID control. Result of the research shows that SMER improved with the increase of products or moisture content in the products.

Another heat pump dryer hybrid done by Bi et al. by combining solar and ground-source to heat pump system as shown in Fig. 11 [100].

Desiccant heat pump shows better performance compare to convention heat pump in term of dehumidifier (drying) and space

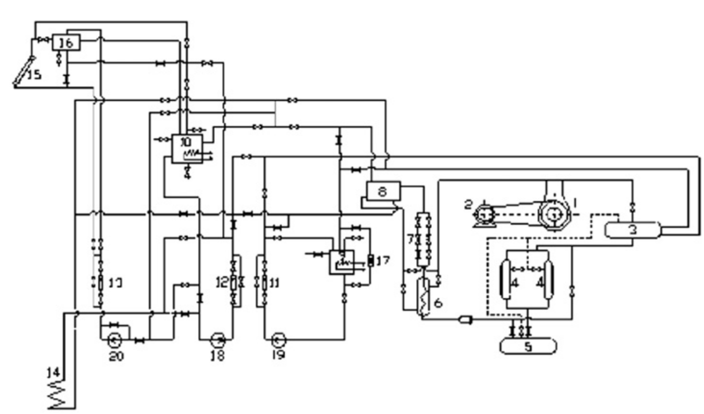


Fig. 1. Solar-ground source heat-pump system flow chart: 1. compressor; 2. motor; 3. condensor; 4. refrigerant surveying instrument; 5. refrigerant collector; 6. heat exchanger; 7. throttle; 8. evaporator; 9. hot-water tank; 10. secondary-fluid tank; 11–13. flowmeters; 14. ground heat-exchanger; 15. solar-energy collector; 16. water tank; 17. fan coil; 18. second-loop medium pump; 19. hot-water pump; 20. piping pump.

Fig. 11. Solar-ground source heat pump system [100].

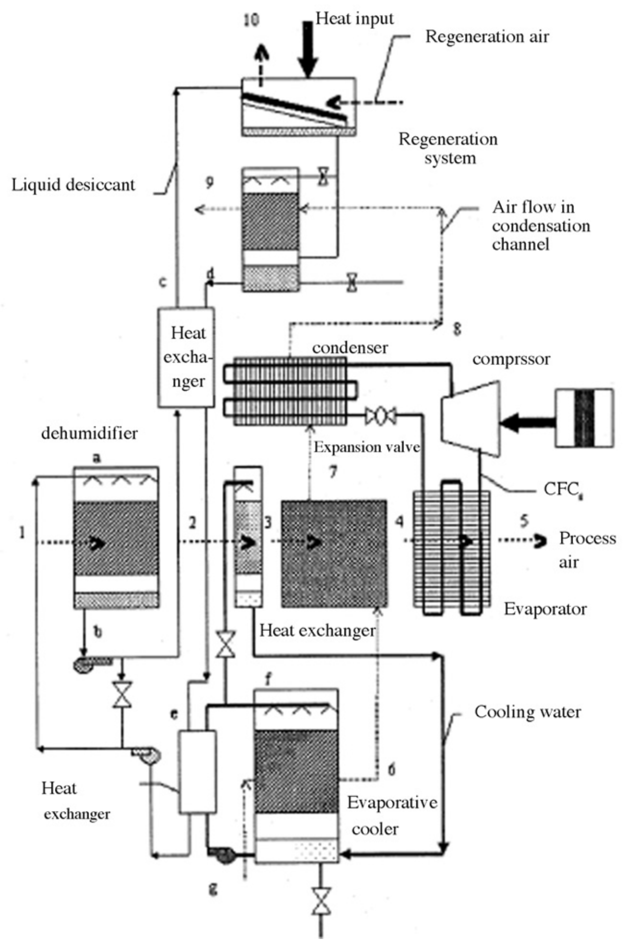


Fig. 12. Desiccant heat pump dehumidifier [102].

heating and cooling control [11,101]. Fig. 12 shows a desiccant heat pump dryer [102].

Solar assisted chemical heat pump dryer has been constructed by Daud in Universiti Kebangsaan Malaysia and tested under Malaysia weather condition [103]. The total energy requirement to maintain drying temperature of 55 °C is 60 kWh. The solar chemical heat pump system contributes 51 kWh which is 85% of total energy required and the rest of 15% energy provided by auxiliary heater. Fig. 13 shows the solar assisted chemical heat pump dryer system.

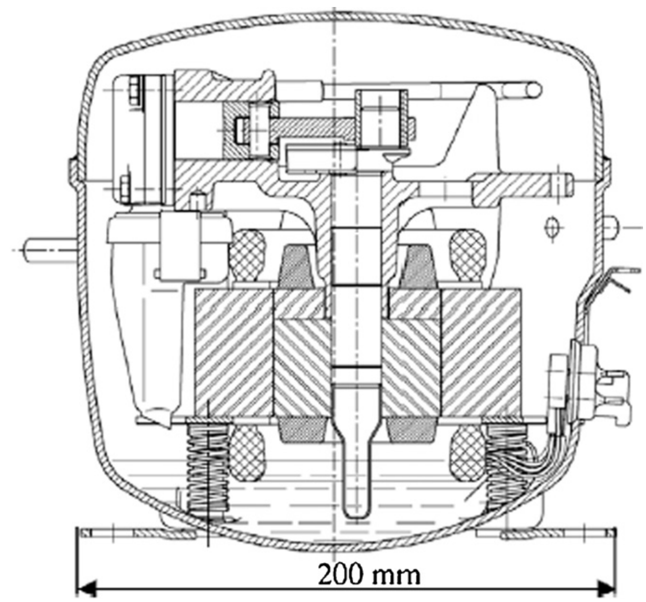


Fig. 14. Compressor cooling with miniature heat pipe.

4. Compressor performance

Though improving heat pump system will improve the dryer condition but compressor performance is also innegligible since compressor is the main component in any heat pump system. Improving the compressor performance may reduce power input or required. One of the most efficiency ways to improve compressor performance is by cooling. Fig. 14 shows the cooling system modified to a hermetic compressor [104]. The research use 2 miniature heat pipes to do the cooling in compressor. Heat pipe (a) does the

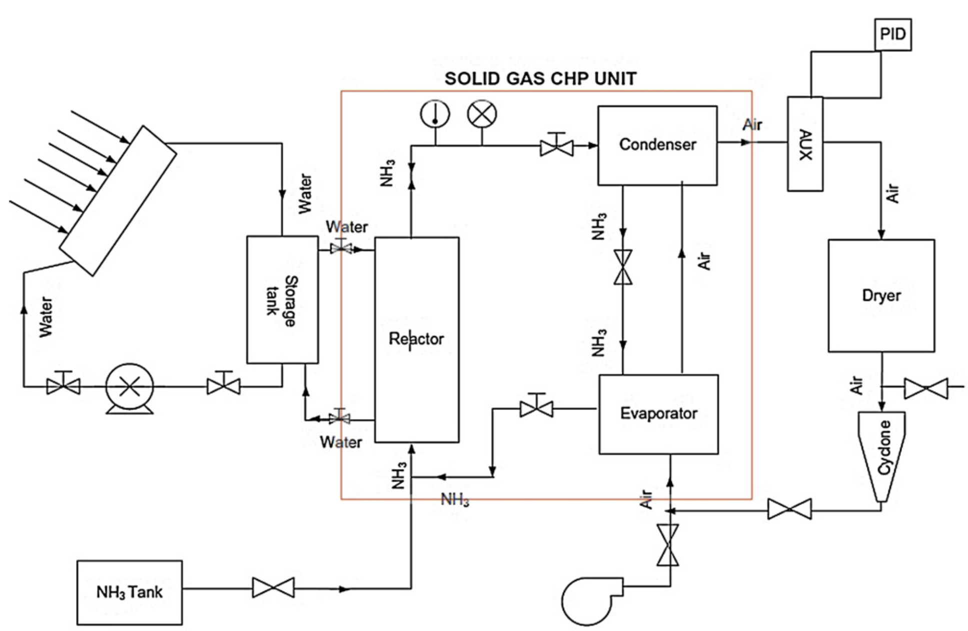


Fig. 13. Solar assisted chemical heat pump dryer.

heat transportation from the compressor cylinder head that is the hottest compressor region to the oil reservoir in the bottom part. The heat pipe (b) transports the heat from the oil to the outside of the compressor.

Using different refrigerant will also affect the performance of the whole heat pump system. Several studies on comparing different refrigerant had been done [105,106].

5. Conclusions

Heat pump is a technology that can produce space heating and cooling efficiently. In this paper, it can be seen that heat pump dryer starts with air source heat pump than improved by hybrid with solar collector, chemical, ground-source and desiccant. The system's developments improve by reducing the depending on electricity produce by fossil fuel and also reduce power input required for drying application. Improving COP of heat pump system is important but performance of SMER and drying condition also innegligible. In development of an energy saving system, system cost, economical factor, system efficiency and performance, system demand and system dependency of fossil fuel is important. Hybrid more technology might increase the system performance but will also increase the cost greatly.

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